Cathodic plasma / bare-tether contact through low Work function coating

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Bare (uninsulated) tethers eliminated need for electron collector at anodic end.

Convenience of using bare tethers with no recourse to a plasma contactor (hollow cathode) at cathodic end carries bare-tether concept to its full completion.

Ion collection along a cathodic segment is a poor replacement for a Hollow Cathode.

Thermionic electron emission from materials with low Work function *W* may be a good replacement.

A low Work function material, C12A7:e^-, developed and studied at the University of Tokyo by the Prof. H. Hosono group, presents a potential value *W* = 0.6 eV, at stable temperatures.

This goes well beyond standard material values well over 2 eV.

Coating a tether with C12A7:e^- would allow efficient thermionic emission, and so cathodic contact plasma/tether, at reasonable working temperatures.

Thermionic emission is different from hollow-cathode emission in important respects concerning a tether system:

a) Just electrons rather than plasma are emitted;

b) Cylindrical rather than spherical geometry is involved: the first geometry allows for OML current of attracted species, following an explicit law, the second one does not.

c) A single, definite physical (Richardson-Dushman) law for emission current is involved, which is not the case for a hollow cathode, for which broadly different regimes may exist, giving rise to quite different schemes/analyses;

d) Hollow cathode emission occurs at just a point in the tether, thermionic emission occurs over a long segment of tether under a range of voltage-bias values.

e) Use of laboratory tests results in designing HC for use in space is tricky.

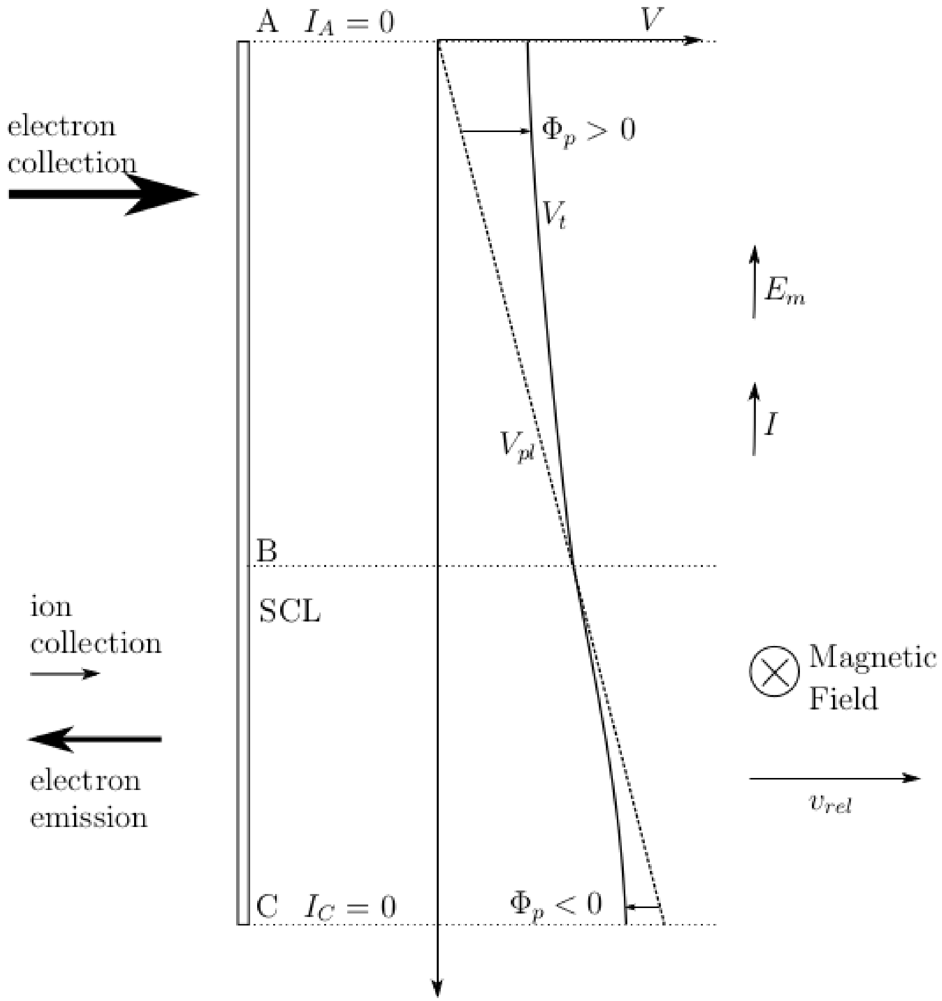
Electrons are emitted, ions collected (picking one electron each), in the cathodic segment BC.

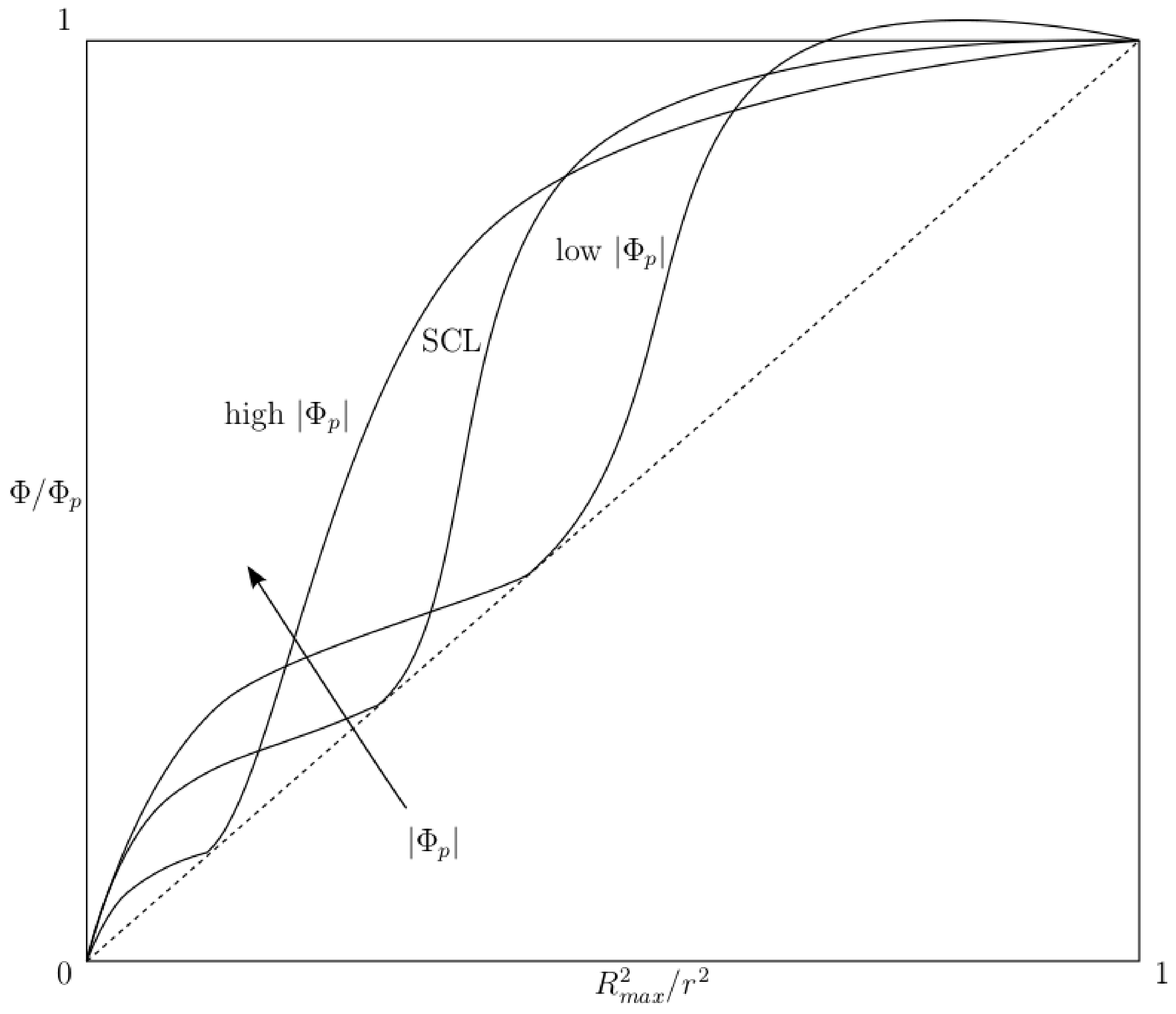
Electrons are collected in the anodic segment AB.

Current vanishes at both ends.

Thermionic emission, which is bias independent, is unaffected below bias for space-charge-limited emission.

From there to the zero-bias point B, the potential is radially non-monotonic.





1
0
1
Φ/Φ_p
R_{max}^2/r^2
low $|\Phi_p|$
SCL
high $|\Phi_p|$
$|\Phi_p|$

Emitted electrons density negligible beyond the sheath; use results from (Phys. Plasmas, 6, 395, 1999). Use high-bias OML current, at R_{max} for OML validity

$$I_i = L \times 2 R_{\max} e N_\infty \sqrt{2e\left|\Phi_p\right| / m_i}$$

$$r_{sh} \approx r_2 \approx r_1 \approx R_{\max} \times \sqrt{\frac{1}{\sigma_1}} \times \sqrt{\frac{e\left|\Phi_p\right|}{kT}}, \qquad \sigma_1 \approx 0.24 \qquad \textbf{for } T_e = T_i \equiv T$$

$$\frac{N_i}{N_\infty} = \frac{\kappa}{\pi} \frac{R_{\max}}{r} \sqrt{\frac{\Phi_p}{\Phi}}, \qquad \kappa(T_i / T_e = 1) \approx 3$$

$$\Rightarrow \quad N_i = \kappa \frac{I_i}{L\, 2\pi r\, e} \sqrt{\frac{m_i}{2e\Phi}}$$

Incoming ions density corresponds to a fluid (radial-motion) model except for the κ factor representing angular momentum effects.

Thermionic emission follows the Richardson-Dushman law

$$I_e = C \times L\, 2\pi R_{\max} \times T_t^2 \exp\left(\frac{W}{kT_t}\right), \qquad C \equiv \frac{4\pi m_e k^2 e}{h^3} \approx 1.202\times 10^6 \frac{A}{m^2 K^2}$$

For simplicity in this first analysis, use fluid model even if failing near the probe:

$$N_e = \frac{I_e}{L\, 2\pi r\, e}\sqrt{\frac{m_e}{2e\left|\Phi_p - \Phi\right|}}$$

Poisson equation reads

$$\frac{1}{r}\frac{d}{dr} r \frac{d\Phi}{dr} = \frac{1}{\varepsilon_0}\left(N_i e - N_e e\right) = \frac{1}{L\, 2\pi r\, \varepsilon_0}\left[\frac{\kappa I_i \sqrt{m_i}}{\sqrt{2e|\Phi|}} - \frac{I_e \sqrt{m_e}}{\sqrt{2e\left|\Phi_p - \Phi\right|}}\right]$$

Introducing $\rho = \ln\left(\frac{r_{sh}}{r}\right)$ **and** $\varphi \equiv \frac{\Phi}{\Phi_p}$**, and using *$I_i$*, *$I_e$*, it results in**

$$\frac{d^2\varphi}{d\rho^2} = e^{-\rho} j_0 \left[\frac{1}{\sqrt{\varphi}} - \frac{\mu}{\sqrt{1-\varphi}} \right]$$

$$\mu \equiv \frac{I_e \sqrt{m_e}}{\kappa I_i \sqrt{m_i}} \equiv \frac{\pi}{\kappa} \frac{C T_t^2 e^{-W/kT}}{e N_\infty \sqrt{2e\left|\Phi_p\right|/m_e}}$$

$$j_0 \equiv \frac{r_{sh} \kappa I_i \sqrt{m_i}}{L\, 2\pi\varepsilon_0 \left|\Phi_p\right| \sqrt{2e\left|\Phi_p\right|}} \equiv \frac{R_{\max}^2}{R_J^2}, \qquad R_J^2 \equiv \frac{\pi\sqrt{\sigma_1}}{\kappa} \sqrt{\frac{kT}{e\left|\Phi_p\right|}} \frac{\varepsilon_0 \left|\Phi_p\right|}{e N_\infty}$$

Both μ and R_J are known for given W, T_p, N_∞, T, m_i, and a selected bias Φ_p. The corresponding value R_{max} is unknown, however.

The equation for φ must be integrated for a tentative R_{max} under conditions at $\rho=0$, i.e. $r=r_{sh}$, for matching to two thin layers beyond the sheath (1999 paper). The value R_{max} must allow satisfying condition $\Phi=\Phi_p$ at $r=R_{max}$.

Solve for ϕ from $\dfrac{d^2\varphi}{d\rho^2} = e^{-\rho}\dfrac{R_{\max}^2}{R_J^2}\left[\dfrac{1}{\sqrt{\varphi}} - \dfrac{\mu}{\sqrt{1-\varphi}}\right],\ \varphi = \dfrac{d\varphi}{d\rho} = 0 \quad at \quad \rho = 0.$

The condition for R_{max} reads $\phi(\rho_p, \mu, R_{max}/R_J)=1$, $\rho_p=ln\sqrt{(e\Phi_p/\sigma_1 kT)}$.

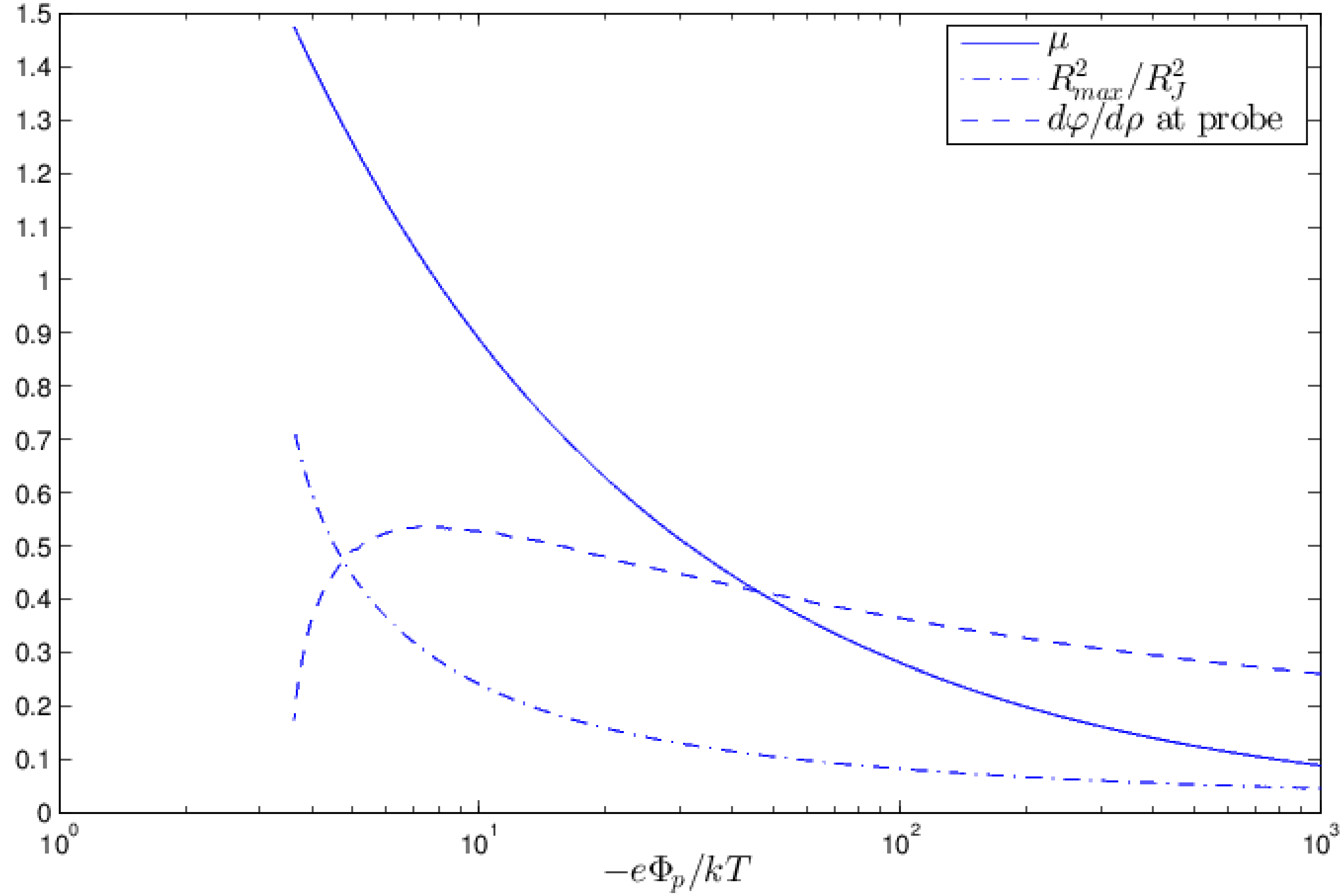
R_{max} is solved for each Φ_p. Decreasing $|\Phi_p|$, until that more dereases of it would result in negative derivative at the probe, SCL condition is reached.

Results on μ, R_{max}/R_J and $d\phi/d\rho$ at ρ_p, versus Φ_p, are shown for values:

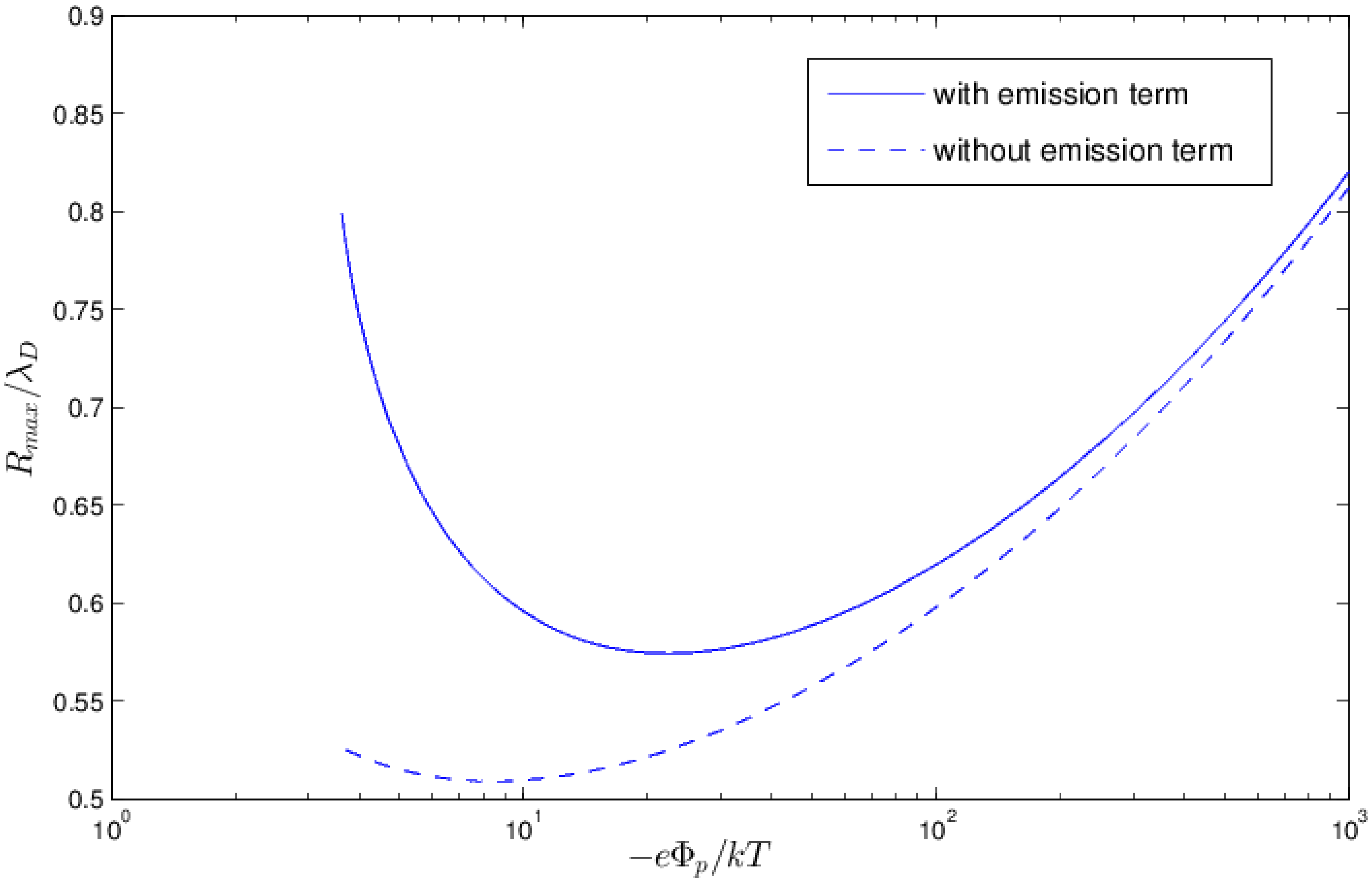
W = 0.75 eV, T_p = 300K, $N_\infty = 3 \times 10^{11}/\text{m}^3$, T = 0.1 eV, oxygen ion-mass.

Also shown is R_{max}/λ_D.

Clear effects are: Emission increases the range of radius R for OML validity; Space-Charge-Limit current (where $d\phi/d\rho\,|_{\rho p}=0$) occurs at very low bias.



μ
R^2_{max}/R^2_J
$d\varphi/d\rho$ at probe
$-e\Phi_p/kT$



with emission term
without emission term
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
R_{max}/λ_D
10^0
10^1
10^2
10^3
$-e\Phi_p/kT$